Nitrogen Oxide Abatement by Distributed Fuel Addition

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ABSTRACT

A screening study was performed on a laboratory scale downfired combustor to determine the effect of various variables on the effectiveness of the reburning process as a technique for NO_x abatement. The objective was to define optimum conditions under which reburning can be used and to be able to compare the reburning performance of our combustor to those reported by others. For this purpose, a statistically designed parametric investigation was conducted to determine how a set of controlled variables (primary and secondary stoichiometric ratios, location of the reburn zone and primary fuel load) would affect the reduction in NO emissions in a classical reburning configuration. Also, the effects of other variables (NO in the primary zone, temperatures in the primary, reburn and burnout zones and the residence time in the reburn zone) were also investigated.

Empirical correlations relating reburning effectiveness to various parameters were derived. These correlations were used to investigate the effect of each individual parameter on reburning effectiveness. An optimum reburn zone stoichiometric ratio was identified at 0.8. At this stoichiometry, a high level of NO reduction (up to 80%) can be achieved beyond which little or no improvement is easily achieved.

INTRODUCTION

The purpose of this project is to achieve a better understanding of the reburning process and to investigate the effect of multiple reburn fuel addition on reburning effectiveness. This requires an understanding of the individual contributions to NO abatement of each of the various variables that are associated with reburning. In order to compare our data to those of others, it is necessary to examine the effects of each variable separately. An efficient way to do this is to employ a statistically correct design of experiments, as described in the previous quarterly report.

The results of tests, performed in a classical reburning configuration (fuel lean primary zone and fuel rich reburn zone), are presented in this report. The primary fuel was Utah Bituminous coal and natural gas was used as reburn fuel.

METHODOLOGY

The test matrix, formulated in the previous quarterly report, placed equal emphasis on the variation of all controlled variables and so only three different values of each variable were considered (two values for reburn zone location). The derived correlations failed to predict an optimum reburn zone stoichiometry, and this gave cause for concern, since such an optimum has been identified by other researchers (Greene et. al., 1985). Therefore, additional experiments were conducted to verify the existence of such an optimum and to allow for greater variation in the reburn zone stoichiometric ratio.

The additional results are combined with those from the original 44 tests to give a total of 82 tests. A statistical model based on this revised test matrix would place more weight on some values of the controlled variables than on others. Thus, the derived models would not have equal predictive powers in all directions. This bias is compensated for by the large number of tests (a total of 82). The test matrix is shown in Table 1. Controlled variables, defined on Table 1a, were allowed in previous work to vary from low to high limits, denoted as -1 and +1 respectively, but now are allowed to vary beyond that range.

Three empirical correlations are fitted to the data using SPSS multiple regression procedure. A description of the derived correlations follows:

1. Equation 1 relates the response (% NO reduction by reburning) to the independent or controlled variables, namely, primary stoichiometric ratio (X3), secondary stoichiometric ratio (X2), location of the reburn zone (X1) and

primary fuel load (X4):

$$Y = 57 - 13.32*X2 + 10.4*X1 - 5.42*X2*X4 - 2.16*X4 - 5.06*X2^2 + 2.72*X2*X3 - 2.03*X2*X1 + 1.68*X3 \quad (1)$$

This equation is used to examine the effects of the controlled variables on the response. All the controlled variables are represented in the equation. Table 2 shows the final step in the regression analysis using STEPWISE method. The equation accounts for 92.3% of the variation among 77 data points.

2. Equation 2 relates the response to the controlled variables in addition to the dependent variables which were measured along with the desired response. These dependent variables are: primary NO level (NOp), primary zone temperature (Tp), reburn zone temperature (Tr), burnout zone temperature (Tb) and reburn zone residence time (RTr). The analysis gives the following equation:

$$Y = 26.1 - 0.01*X2*Tr + 0.092*Tr*RTr - 105*RTr^2 - 5.66*X2*X4 + 0.003*X3*NOp - 3.91*X2^2 + 2.24*X2*X3 \quad (2)$$

Reburn zone location (X1) was not included in the analysis since it is represented by the residence time in the reburn zone. This equation is most general and is useful for comparing the significance of the various parameters. Temperatures in the primary zone (Tp) and in the burnout zone (Tb) do not show any statistical significance and are not represented in the equation. Table 3 shows the final step in the regression analysis using STEPWISE method. The equation accounts for 91.8% of the variation among 82 data points. It must be emphasized that these statistically derived empirical models are valid <u>only</u>

within the variable limits tested. Therefore, the weak dependence on NOp is only valid for NOp values greater than 900 and not for low primary NO values.

3. Equation 3 relates the response to the most significant variables in equations 1 and 2. This allows the list of variables to be narrowed down to three variables, all reburn zone properties, namely, stoichiometric ratio (X2), temperature (Tr) and residence time (RTr). The analysis yields the following equation:

$$Y = 26.2 - 0.053*X2*Tr + 0.083*Tr*RTr - 84.3*RTr^2 + 62*X2 - 3\ 73*X2^2 \qquad (3)$$

Equation 3 is used for a seperate examination of the effects of the three most significant variables mentioned above. Table 4 shows the final step in the regression analysis using STEPWISE method. The equation accounts for 87.3% of the variation among 82 data points.

Figure 1, showing the scatter of the predicted response for the derived correlations, depicts a visual representation of how accurate these empirical models really are. These empirical correlations are then used to study the variation of reburning effectiveness with each fundamental variable. Primary zone temperature (Tp) and burnout zone temperature (Tb) do not seem to have any statistical significance and are assumed to have a minor contribution in the reburning process.

DISCUSSION

Using the derived correlations, plots are generated to show the effect of each individual variable on reburning effectiveness. Furthermore, the results of this study are compared to those published by other researchers. This is done by focusing on the measured effects of one variable at a time, namely primary stoichiometric ratio, primary fuel (Utah Bituminous #2 coal) load, reburn zone stoichiometric ratio, primary NO level, reburn zone temperature and reburn zone residence time.

1. Primary Stoichiometric Ratio:

A number of researchers have shown that the variation in primary stoichiometric ratio has only a small effect on reburning effectiveness with slightly better reduction in NO at lower primary stoichiometric ratios. That may be due to longer residence times at lower primary stoichiometric ratios. Greene et al. (1985) studied the effect of varying the primary stoichiometric ratios at constant residence times and constant primary NO levels. No significant changes in reburning effectiveness were detected. Figure 2 shows a similar trend at reburn zone stoichiometric ratios less than 0.82. However, at less fuel rich reburn zone stoichiometries, greater reduction in NO is observed at higher primary stoichiometric ratio. This result might be misleading, since this figure is based on Equation 1 where, a variation in primary stoichiometric ratio is also accompanied by variations in other factors such as residence time and temperature.

At the same fuel load, reducing primary stoichiometric ratio is accompanied by an increase in reburn zone residence time which is beneficial in reducing NO (Kelly et al., 1983, Mulholland and Hall, 1986 and Overmoe et al., 1986). Furthermore, for reburning to be effective, a high degree of primary fuel burnout is necessary and enough residence time should be allowed in the primary zone (Chen et al., 1986, LaFond and Chen, 1987 and Overmoe et al., 1986). Chen et al. (1986) suggested a residence time requirement of at least 0.3 seconds in the primary zone. Otherwise, oxygen carryover into the reburn zone would result in an actual reburn zone stoichiometric ratio that is leaner than expected, which may result in less NO reduction. This effect is greater at higher levels of primary stoichiometric ratio because of shorter residence times in the primary zone. Thus, in practice, lower primary stoichiometric ratios may appear to improve reburning effectiveness. However, this is a minor factor in this study, since primary zone residence times greater than 0.25 seconds were used for all the tests and this should have allowed sufficient time for primary fuel burnout.

Equation 2 is used to show the effect of primary stoichiometric ratio at constant reburn zone temperature and reburn zone residence time as seen in Figure 3. As in Figure 2, greater reduction in NO is observed at higher primary stoichiometric ratios, especially as the reburn zone becomes more fuel lean. A possible explanation is that as primary stoichiometric ratio is increased, the amount of reburn fuel must also be increased proportionally to maintain a constant reburn zone stoichiometric ratio. This may result in more fuel rich pockets around the reburn fuel jet. Consequently, increasing primary stoichiometric ratio may improve the reburning effectiveness especially when the reburn zone is less fuel rich where this effect is more significant.

In the region where primary stoichiometric ratio has little impact on reburning effectiveness (reburn zone stoichiometric ratios less than 0.82), it would be more desirable to operate the primary zone under low excess air level. This would reduce the amount of reburn fuel required to reach the desired level of reburn zone stoichiometric ratio. On the other hand, a certain amount of oxygen in the reburn zone is necessary for the formation of hydrocarbon radicals from the reburn fuel and to promote the conversion of HCN and NH3. A primary stoichiometric ratio of 1.1 has been recommended by LaFond and Chen (1987).

2. Primary Fuel Load

The dependence of reburning effectiveness on the primary fuel (coal) load (Figure 4) is of minor practical significance since often it is not desirable to vary the fuel load in combustion systems. In this study, the fuel load was varied in order to obtain a wider range of temperatures and residence times. Figure 4 shows that the reburning effectiveness dependence on fuel load diminishes in the vicinity of reburn zone stoichiometric ratio of 0.8. This trend occurs regardless of reburn zone location (Figures 2 and 4) and the primary stoichiometric ratio level (Figure 2). A reburn zone stoichiometric ratio of 0.8 is identified as an optimum in this study.

3. Reburn Zone Stoichiometric Ratio

Reburn zone stoichiometric ratio is a critical parameter in reburning. Literature data on an optimum reburn zone stoichiometry are conflicting and sometimes misleading because other significant effects, such as mixing and temperature need also be considered. Optimum reburn zone stoichiometric ratios ranging from 0.8 to 0.95 were reported in the literature. La Fond and Chen (1987) presented a discussion of the effect of variation in reburn zone stoichiometry and a review of the results of many researchers. Detailed N-species measurements at various reburn zone stoichiometric ratios (Chen et al., 1986, Greene et al., 1985 and Kolb et al., 1988) showed that an optimum would exist as a result of a tradeoff between the destruction of NO from the primary zone and the formation of HCN and NH_3 as reburn zone stoichiometric ratio decreases. The N-species that are formed in the reburn zone are partially converted to NO in the burnout zone. Other studies showed no clear optimum as the reburn zone became more fuel rich (Kelly et al., 1983, Lanier et al., 1986 and Miyamae et al., 1986). It has been suggested by LaFond and Chen (1987) that exceedingly long residence times or lower temperatures could cause a shift in the optimum reburn zone stoichiometric ratio. **Results by a number of researchers suggest that a higher reburn zone temperature can produce an optimum reburning effectiveness at a more fuel rich reburn zone stoichiometric ratio** (Brown and Kuby, 1986, Greene et al., 1985 and Miyamae et al., 1986). A trend of this nature was observed at greater fuel loads which were accompanied by higher temperatures (Figure 4). The effect of temperature is discussed in a separate section.

Reburn **fuel mixing with primary zone effluent is another factor which** may have an **effect [illegible] reburn zone stoichiometric ratio and reburning effectiveness.** Miyamae et al. (1986) suggested that this may be due to the effect of local distribution of O_2, NO and reburn fuel. Furthermore, LaFond and Chen (1987), hypothesized that improved mixing might result in sharper reburn zone stoichiometric ratio optima. In short, the method by which the reburn fuel is introduced may have an effect on the location of an optimum reburn zone stoichiometry.

In this study, none of the derived correlations could predict an optimum reburn zone stoichiometric ratio. Detailed experiments were performed to investigate the effect of reburn zone stoichiometric ratio on reburning effectiveness and the results are presented in Figures 5 and 6. Figure 6 shows an optimum reburn zone stoichiometric ratio at about 0.8. As reburn zone stoichiometric ratio is reduced below this value, little or no further improvement in reburning effectiveness is detected. Equation 1 is plotted to compare the predicted response (percentage in NO reduction by reburning) to the data presented in Figure 5 and 6 and a reasonable fit is obtained.

To summarize, reburn zone temperatures and residence times, and mixing of the reburn fuel with the effluent of the primary zone are all factors which may have an effect on the location of an optimum reburn zone stoichiometry. A value of 0.8 was found from our experiments, although this is not predicted from an empirical model that best fits the data.

4. Primary NO Level

Primary NO levels range from 920 to 1210 ppmv in this study. Equation 2 is used to show the effect of the primary NO on reburning effectiveness in this limited range as seen in Figure 7. It is obvious that the effect of primary NO is of little significance in the tested range and can be ignored. Some studies (Brown et al., 1986 and Greene et al., 1985) have shown that reburning effectiveness decreases with primary NO for initial levels below 600 ppm. But at higher levels (greater than 600 ppm), minor changes in reburning effectiveness were observed. This is in agreement with the observations of this study where levels were high. For nitrogen free reburn fuels, the destruction of NO decreases as primary NO increases but the formation of NO from the total fuel nitrogen exiting the reburn zone is only weakly dependent on the initial level. This is likely due to greater hydrocarbon-NO interaction at higher primary NO levels according to the path:

$$CH + NO \longrightarrow HCN + O$$

Miyamae et al. (1986) suggested that the ratio of the concentration of hydrocarbons from reburn fuel to that of primary NO is a significant factor, and by holding this ratio constant, the same reburning effectiveness could be achieved at any primary NO level. However, this conclusion was based on a limited number of observations and needs to be further verified.

To summarize, reburning effectiveness is not expected to have a significant dependence on primary NO levels greater than initial levels of 600 ppm. In this study, the effect of the primary NO level shows weak statistical significance in the tested range (900-1200 ppm) and can be neglected.

5. Reburn Zone Temperature

Reburn zone temperature is a parameter which has a significant effect on reburning effectiveness. In previous studies, reburning has been investigated within temperature ranges that are applicable to large scale boilers (1100-1400 C). In this work, reburn zone temperatures lie within a range of 1000 C to 1400

C. Equation 3 is used to investigate the effect of reburn zone temperature at different residence times. Figure 8 shows that **higher reburn zone temperatures would improve reburning effectiveness if the reburn zone is rich enough, depending on the residence time**. Also, at lower reburn zone temperatures, the curves are less steep which indicates that an optimum configuration can be identified at less fuel rich reburn zone stoichiometric ratio as mentioned earlier.

There is a minimum residence time requirement for an increase in reburn zone temperature to be beneficial at a given reburn zone stoichiometric ratio (Figure 8). This is to be expected since a higher reburn zone temperature promotes the decay of NO in the reburn zone and sufficient time must be allowed for the decay of other N-species (Miyamae et al., 1986). Nevertheless, in the range of the optimum reburn zone stoichiometric ratio (less than or equal to 0.8), higher reburn zone temperatures would result in greater reburning effectiveness regardless of reburn zone residence time. This is in agreement with the results of various studies (Brown and Kuby, 1986, Greene et al., 1985 and Miyamae et al., 1986). These studies suggest that higher reburn zone temperature would improve reburning effectiveness and might cause a shift in the optimum reburn zone stoichiometric ratio to the more fuel rich side because of larger reductions in the total fuel nitrogen in the reburn zone (less HCN).

On the other hand, Figure 8 also shows that cooler reburn zone temperatures might be more beneficial if the reburn zone is close to being fuel lean, especially in the low reburn zone residence time range (less than 0.4 seconds). Similar trends were shown by Greene et al. (1985). In short, the effect of a change in reburn zone temperature on reburning effectiveness would depend on reburn zone stoichiometric ratio and the residence time that is allowed in the reburn zone.

Chen et al. (1983, 1986) discussed the effect of cooling the reburn zone in the case of coal reburning. The trend was opposite to that of methane reburning and a better reburning effectiveness was observed at a lower reburn zone temperature. That was attributed to NO reduction by NHi which is favored in the low temperature range of 800-1000 C. Another possible explanation is that at lower reburn zone temperatures, reburn coal would produce more hydrocarbon radicals and less H_2 and CO_2. Volatile matter from coal have been shown to be a better reburn fuel at lower coal pyrolysis temperatures (Miyamae et al., 1986). The use of coal as a reburn fuel will be tested in the second phase of this project.

Figure 8 is significant, since it shows that certain directional trends (with respect to reburn zone temperature, for example) depend strongly on other variables, such as reburn stoichiometric ratio and residence time. This complexity has made it difficult to compare results from various authors in the past, and demonstrates the need for a comprehensive study such as the one performed here.

6. Reburn Zone Residence Time

There are two residence times that are important to the reburning process: residence time in the primary zone and that in the reburn zone. The significance of the residence time in the primary zone was discussed in a previous section. Times ranging from 0.085 seconds to 0.85 seconds were used in this study. Equation 3 is used to investigate the effect of reburn zone residence time at different reburn zone temperatures as shown in Figures 9 and 10. As expected, **longer reburn zone residence time improved reburning effectiveness and the effect of residence time is significantly greater at higher reburn zone temperatures**. Figure 10 shows that there is a temperature dependent limiting time beyond which no further improvement in reburning effectiveness is possible. In the reburn zone, longer residence times are accompanied by greater decay of N-species before they enter the burnout zone (Lanier et al., 1986 and Miyamae et al., 1986). Furthermore, at higher primary NO levels, longer residence times may be necessary for hydrocarbon-NO interaction in the reburn zone. Therefore, as reburn zone residence time is increased, the reburning effectiveness also increases. However, there exists a temperature dependent asymptotic value beyond which no increase in residence time is beneficial.

As discussed earlier, reburn zone temperature and reburn zone residence time interactions have a significant impact on reburning effectiveness. Equation 3 is used to produce contour plots for reburning effectiveness as a function of reburn zone temperature and reburn zone residence time (Figure 11) at reburn zone stoichiometric ratio of 0.8. The data points shown in the lower half of Figure 11 show the range of the experimental parameters that were measured. These contour plots show that each level of NO reduction has a minimum residence time requirement and a minimum temperature requirement, both of which increase at higher levels of reburning effectiveness. **At lower reburn zone residence time (less than 0.4 seconds), time is the dominant factor. While at higher reburn zone residence time, (greater than 0.5 seconds), temperatures become the dominant factor. Thus, the effects of reburn zone temperature and** residence time are interdependent and their effects cannot be treated separately.

CONCLUSIONS & FUTURE WORK

A comprehensive screening study for classical reburning was performed and the effects of various variables that are associated with reburning were analyzed. Empirical models correlating reburning effectiveness with the various variables were derived. These models were used to show the effect of each individual variable on reburning effectiveness. A weak optimum was identified at a reburn zone stoichiometric ratio of 0.8 at which reburning can be performed under conditions that would minimize the contributions of primary stoichiometric ratio and primary fuel load and thus allow greater control of the reburning process. In general, the results of this study agreed with those of other investigators.

The next step in this study is to investigate the effects of fuel lean reburning (SR2 greater than 1) and reburning in the post flame of a rich primary flame (SR1 smaller than 1). Both of these processes occur under advanced (multistage) reburning conditions. The completed screening study would provide important information regarding the reduction of NO by distributed reburn fuel addition. It is expected that by distributing the reburn fuel down the combustor, further reduction in NO can be achieved by slowing down the consumption of the reburn fuel and the generation of free radicals that cause the destruction of the nitrogenous species.

REFERENCES

Brown, R. A. and W. C. Kuby, "Application of Reburning for NO_x Control in Cogeneration", p. 26-1, Proceedings of the 1985 Joint Symposium on Stationary Combustion NO_x Control, Volume 1, EPRI Report CS-4360, January 1986.

Chen, S. L., W. C. Clark, M. P. Heap, D. W. Pershing and W. R. Seeker, "NO_x Reduction by Reburning with Gas and Coal - Bench Scale Studies", Proceedings of the 1982 Joint Symposium on Stationary Combustion NO_x Control, Volume 1, EPRI Report CS-3182, July 1983.

Chen, S. L., J. M. McCarthy, W. D. Clark, M. P. Heap, W. R. Seeker and D. W. Pershing, "Bench and Pilot Scale Process Evaluation of Reburning for In-Furnace NO_x Reduction", Twenty-first Symposium (International) on Combustion, p. 1159, The Combustion Institute, Pittsburgh, Pennsylvania (1986).

Greene, S. B., S. L. Chen, W. D. Clark, M. P. Heap, D. W. Pershing and W. R. Seeker, "Bench-Scale Process Evaluation of Reburning and Sorbent Injection for In-Furnace NOx/SOx Reduction", U.S. EPA Report EPA-600/7-85-012, March 1985.

Kelly, J. T., R. L. Pam and S. T. Suttmann, "Fuel Staging for Pulverized Coal Furnace NO_x Control", p. 17-1, Proceedings of the 1982 Joint Symposium on Stationary Combustion NO_x Control, Volume 1, EPRI Report CS-3182, July 1983.

Kolb, T., P. Jansohn and W. Leuckel, "Reduction of NO_x Emission in Turbulent Combustion by Fuel-Staging / Effects of Mixing and Stoichiometry in the Reduction Zone", paper presented at the Twenty-second Symposium (International) on Combustion, The Combustion Institute, Seattle, Washington (1988).

La Fond, J. F. and S. L. Chen, "An Investigation to Define the Physical/Chemical Constraints which Limit NOx Emission Reduction Achievable by Reburning", U.S. DOE Quarterly Report DE-AC22-86PC91025, May 1987.

Lanier, W. S., J. A. Mulholland and J. T. Beard, "Reburning Thermal and Chemical Processes in a Two-Dimensional Pilot-Scale System", Twenty-first Symposium (International) on Combustion, p. 1171, The Combustion Institute, Pittsburgh, Pennsylvania (1986).

Miyamae, S., H. Ikebe, K. Makino, K. Suzuki and J. Mogi, "Evaluation of In-Furnace NO_x Reduction", p. 24-1, Proceedings of the 1985 Joint Symposium on Stationary Combustion NO_x Control, Volume 1, EPRI Report CS-4360, January 1986.

Miyamae, S., T. Kiga, H. Ikebe and K. Suzuki, "Experimental Study on NOx Destruction Characteristics by Reburning of Pulverized Coal", paper presented at the 1986 Fall Meeting of Western State Section/ The Combustion Institute, Tucson, Arizona, October 1986.

Mulholland, J. A. and R. E. Hall, "The Effect of Fuel Nitrogen in Reburning Application to a Firetube Package Boiler," p. 22-1, Proceedings of the 1985 Joint Symposium on Stationary Combustion NO_x Control, Volume 1, EPRI Report CS-4360, January 1986.

Overmoe, B. J., J. M. McCarthy, S. L. Chen, W. R. Seeker, G. D. Silcox and D. W. Pershing, "Pilot Scale Evaluation of NO_x Control from Pulverized Coal Combustion by Reburning", p. 21-1, Proceedings of the 1985 Joint Symposium on Stationary Combustion NO_x Control, Volume 1, EPRI Report CS-4360, January 1986.

TABLE 1

RAW DATA

RUN	INJ	SR2	SR1	COAL		ppm	°K	°K	°K	sec
	X1	X2	X3	X4	RESP	NO, p	T, p	T, r	T, b	(RT)r
RS# 0A	1.000	-0.700	1.000	1.130	78.59	1210	1667	1645	1564	0.246
RS# 0B	-1.000	-0.700	1.000	1.130	54.47	1200	1653	1581	1544	0.094
RS# 1A	1.000	-1.000	1.000	1.130	79.38	1140	1667	1645	1564	0.245
RS# 1B	-1.000	-1.000	1.000	1.130	57.10	1140	1653	1581	1544	0.085
RS# 2A	1.000	0.000	-0.200	1.130	64.47	977	1694	1677	1542	0.312
RS# 2B	-1.000	0.000	-0.200	1.130	36.67	977	1686	1588	1550	0.127
RS# 3A	1.000	-1.000	1.000	1.130	80.28	1090	1614	1622	1546	0.250
RS# 3B	-1.000	-1.000	1.000	1.130	60.55	1090	1549	1562	1547	0.085
RS# 4A	1.000	1.000	1.000	1.130	43.36	1090	1620	1637	1536	0.327
RS# 4B	-1.000	1.000	1.000	1.130	30.29	1090	1546	1529	1517	0.122
RS# 6A	1.000	0.000	0.000	0.865	65.70	1090	1628	1621	1474	0.344
RS# 6B	-1.000	0.000	0.000	0.865	38.44	1090	1598	1539	1518	0.124
RS# 7A	1.000	-1.000	-1.000	0.865	77.84	1130	1658	1617	1468	0.329
RS# 7B	-1.000	-1.000	-1.000	0.865	56.37	1130	1683	1576	1503	0.113
RS# 8A	1.000	1.000	-1.000	0.865	30.72	1020	1656	1635	1487	0.432
RS# 8B	-1.000	1.000	-1.000	0.865	22.43	1020	1661	1550	1490	0.162
RS# 9A	1.000	-1.000	0.000	0.005	76.22	975	1552	1534	1437	0.388
RS# 9B	-1.000	-1.000	0.000	0.005	57.02	975	1572	1491	1451	0.131
RS#10A	1.000	1.000	0.000	0.005	47.72	985	1572	1569	1475	0.492
RS#10B	-1.000	1.000	0.000	0.005	31.94	985	1577	1501	1482	0.185
RS#11A	1.000	0.000	0.000	0.005	66.07	1030	1569	1570	1511	0.432
RS#11B	-1.000	0.000	0.000	0.005	43.81	1030	1569	1505	1477	0.146
RS#12A	1.000	1.000	0.000	-0.074	43.34	1020	1461	1453	1335	0.555
RS#12B	-1.000	1.000	0.000	-0.074	33.31	1020	1458	1362	1338	0.208
RS#13A	1.000	0.000	0.000	-0.074	67.49	1030	1513	1495	1363	0.475
RS#13B	-1.000	0.000	0.000	-0.074	44.67	1030	1503	1406	1362	0.174
RS#14A	1.000	0.000	1.000	-0.074	62.12	1040	1475	1500	1423	0.428
RS#14B	-1.000	0.000	1.000	-0.074	43.74	1040	1471	1434	1418	0.153
RS#15A	1.000	0.000	-1.000	-0.074	73.11	950	1534	1505	1360	0.523
RS#15B	-1.000	0.000	-1.000	-0.074	36.06	950	1559	1458	1393	0.192
RS#16A	1.000	-1.000	1.000	-1.132	65.68	965	1418	1411	1297	0.569
RS#16B	-1.000	-1.000	1.000	-1.132	49.41	965	1407	1319	1301	0.197
RS#17A	1.000	1.000	1.000	-1.132	62.80	1000	1436	1427	1289	0.740
RS#17B	-1.000	1.000	1.000	-1.132	42.20	1000	1430	1327	1306	0.278
RS#18A	1.000	-1.000	1.000	-0.934	69.69	1070	1433	1425	1317	0.521
RS#18B	-1.000	-1.000	1.000	-0.934	55.05	1070	1424	1345	1307	0.180
RS#19A	1.000	1.000	1.000	-0.934	55.41	1100	1432	1429	1306	0.685
RS#19B	-1.000	1.000	1.000	-0.934	49.39	1100	1426	1338	1319	0.256

RS#20A	1.000	0.000	0.000	-0.934	73.55	1090	1474	1443	1307	0.655
RS#20B	-1.000	0.000	0.000	-0.934	48.48	1090	1434	1337	1323	0.240
RS#21A	1.000	-1.000	-1.000	-0.915	69.62	1000	1488	1439	1278	0.634
RS#21B	-1.000	-1.000	-1.000	-0.915	58.43	1000	1473	1335	1294	0.224
RS#22A	1.000	1.000	-1.000	-0.915	45.30	995	1503	1435	1209	0.851
RS#22B	-1.000	1.000	-1.000	-0.915	40.50	995	1505	1313	1227	0.331
MR# 9	1.000	-0.360	-0.240	-0.332	74.18	1034	1553	1524	1408	0.485
MR# 10	0.335	-0.360	-0.240	-0.332	70.31	1034	1554	1495	1448	0.384
MR# 11	-1.000	-0.360	-0.240	-0.332	46.81	1034	1545	1443	1429	0.174
MR# 27	1.000	-0.360	-0.240	-0.332	73.57	1192	1553	1524	1408	0.542
MR# 29	0.335	-0.360	-0.240	-0.332	71.73	1192	1554	1495	1448	0.419
MR# 30	-1.000	-0.360	-0.240	-0.332	46.56	1192	1545	1443	1429	0.183
MR# 14	-1.000	1.160	-0.240	-0.306	17.03	1133	1457	1271	1167	0.270
MR# 15	1.000	0.760	-0.240	-0.306	57.40	1129	1510	1457	1301	0.595
MR# 16	-1.000	0.760	-0.240	-0.306	35.25	1129	1483	1299	1271	0.232
MR# 17	1.000	0.360	-0.240	-0.306	66.43	1126	1523	1488	1315	0.554
MR# 18	-1.000	0.360	-0.240	-0.306	40.50	1126	1514	1357	1305	0.213
MR# 19	1.000	-0.040	-0.240	-0.306	71.56	1111	1522	1483	1367	0.514
MR# 20	-1.000	-0.040	-0.240	-0.306	42.39	1111	1513	1381	1347	0.192
MR# 21	1.000	-0.360	-0.240	-0.306	75.42	1123	1532	1497	1373	0.492
MR# 22	0.335	-0.360	-0.240	-0.306	68.39	1123	1534	1475	1405	0.389
MR# 23	-1.000	-0.360	-0.240	-0.306	48.17	1123	1515	1382	1355	0.179
UB# 5	1.000	0.360	-1.000	-1.340	57.99	907	1481	1411	1298	0.606
RV# 3	1.000	0.760	-1.240	0.794	35.93	984	1614	1580	1385	0.460
RV# 8	1.000	0.360	-1.240	0.794	56.43	945	1624	1589	1410	0.431
RV# 18	1.000	-0.360	-1.240	0.794	79.43	933	1656	1569	1478	0.373
RV# 14	1.000	-0.840	-1.240	0.794	80.45	980	1635	1577	1453	0.356
RV# 12	1.000	-1.112	-1.240	0.794	77.61	923	1628	1576	1422	0.350
RV# 6	0.335	0.760	-1.240	0.794	37.13	984	1623	1549	1400	0.368
RV# 7	0.335	0.360	-1.240	0.794	52.39	945	1631	1561	1433	0.342
RV# 16	0.335	-0.360	-1.240	0.794	74.08	933	1660	1573	1495	0.298
RV# 15	0.335	-0.840	-1.240	0.794	74.21	980	1638	1549	1469	0.284
RV# 10	0.335	-1.112	-1.240	0.794	74.19	923	1634	1546	1482	0.274
RV# 1	-1.000	1.160	-1.240	0.794	21.90	1041	1611	1444	1350	0.193
RV# 2	-1.000	0.760	-1.240	0.794	23.72	984	1617	1454	1388	0.176
RV# 9	-1.000	0.360	-1.240	0.794	31.82	945	1645	1487	1425	0.161
RV# 17	-1.000	-0.360	-1.240	0.794	48.18	933	1654	1542	1512	0.135
RV# 13	-1.000	-0.840	-1.240	0.794	54.66	980	1635	1520	1469	0.126
RV# 11	-1.000	-1.112	-1.240	0.794	50.93	923	1645	1517	1455	0.121
MR# 28		-0.360	-0.240	-0.332	58.37	1097	1553	1524	1448	0.316
RV# 4		0.760	-1.240	0.794	32.24	984	1614	1588	1481	0.283
RV# 19		-0.360	-1.240	0.794	69.51	933	1656	1619	1539	0.243
RV# 20		-0.360	-1.240	0.794	32.96	933	1656	1608	1592	0.087
RV# 5		0.760	-1.240	0.794	32.24	984	1623	1523	1449	0.189

TABLE 1a.
CONTROLLED VARIABLES

Variable
1. location of reburn fuel injection, distance from burner in inches
2. reburn zone stoichiometric ratio, SR2
3. primary zone stoichiometric ratio, SR1
4. primary fuel load (Utah Bituminous #2 coal), lb/hr

Variable	Code	Low Limit	High Limit	Coding Equation
1	X1	39 (port 5)	21 (port 3)	X1=(var-30)/-9
2	X2	0.73	0.98	X2=(var-0.855)/0.125
3	X3	1.1	1.35	X3=(var-1.225)/0.125
4	X4	2.5	4.5	X4=(var-3.5)/1.0

Y is the desired response expressed as the percentage of NO reduction due to reburning:

$$Y = 100 - 100 * (NO_{ex}/NO_p)$$

NO_{ex} = ppmv NO (dry, corrected) in exhaust
NO_p = ppmv NO (dry, corrected) in primary zone (before reburn fuel is introduced)

ppm NO (corrected) = ppm NO (measured) * [(actual moles/h flue gas at measuring point)/(moles/h flue gas for coal only burned at SR1=1)]

TABLE 2

*** * * * M U L T I P L E   R E G R E S S I O N * * * ***

Equation Number 1

Multiple R	.96087
R Square	.92327
Adjusted R Square	.91424
Standard Error	4.86377

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	8	19356.40449	2419.55056
Residual	68	1608.62828	23.65630

F = 102.27934   Signif F = .0000

------------------ Variables in the Equation ------------------

Variable	B	SE B	95% Confdnce Intrvl B		Beta	F	Sig F
X2	-13.320589	.770261	-14.857621	-11.783558	-.600269	299.069	.0000
X1	10.423297	.585140	9.255668	11.590925	.601693	317.315	.0000
X2X4	-5.424480	.949665	-7.319507	-3.529453	-.205447	32.627	.0000
X4	-2.156119	.779686	-3.711959	-.600278	-.098286	7.647	.0073
X2X2	-5.058348	1.226983	-7.506755	-2.609940	-.141690	16.996	.0001
X2X3	2.717070	.845997	1.028908	4.405231	.116004	10.315	.0020
X1X2	-2.026686	.775384	-3.573942	-.479431	-.088319	6.832	.0110
X3	1.680924	.727679	.228863	3.132985	.032755	5.336	.0239
(Constant)	56.989658	.903937	55.185879	58.793437		3974.801	.0000

------------ Variables not in the Equation ------------

Variable	Beta In	Partial	Min Toler	F	Sig F
X1X3	-.038504	-.135772	.864484	1.258	.2660
X1X4	.038233	.135331	.862519	1.250	.2676
X3X4	.009383	.030773	.791772	.064	.8018
X3X3	.020140	.058848	.655105	.233	.6310
X4X4	.004707	.014858	.764572	.015	.9036

TABLE 3

*** * * *   M U L T I P L E   R E G R E S S I O N   * * * ***

Equation Number 2

Multiple R	.95838
R Square	.91849
Adjusted R Square	.91078
Standard Error	4.99661

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	7	20819.74018	2974.24860
Residual	74	1847.49570	24.96616

F =   119.13121   Signif F = .0000

------------------ Variables in the Equation ------------------

Variable	B	SE B	Beta	T	Sig T
X2TR	-.010419	5.4479E-04	-.684644	-19.125	.0000
TRRTR	.091909	.007388	1.405046	12.441	.0000
RTRRTR	-105.047413	13.729175	-.871580	-7.651	.0000
X2X4	-5.662462	.993273	-.209815	-5.701	.0000
X3NOP	.003139	6.9009E-04	.157051	4.549	.0000
X2X2	-3.911447	1.247535	-.107038	-3.135	.0025
X2X3	2.243729	.849052	.094690	2.643	.0100
(Constant)	26.125306	2.164796		12.068	.0000

------------- Variables not in the Equation -------------

Variable	Beta In	Partial	Min Toler	T	Sig T
X2	.221179	.029398	.001402	.251	.8023
X3	-.622674	-.144984	.004394	-1.252	.2146
X4	.031202	.084970	.069394	.729	.4686
NOP	.008054	.023939	.084684	.205	.8385
TP	.044017	.112362	.071334	.966	.3372
TR	.019839	.059354	.069409	.508	.6130
TB	.035844	.099725	.071818	.856	.3946
RTR	-.147112	-.041196	.006391	-.352	.7256
X3X3	.042015	.125560	.084867	1.081	.2831
X4X4	.049717	.155038	.083521	1.341	.1841
NOPNOP	.007882	.023504	.084670	.201	.8414
TPTP	.043147	.110492	.071465	.950	.3453
TRTR	.018713	.055728	.068469	.477	.6349
TBTB	.034107	.095341	.072452	.818	.4158
X2NOP	-.217712	-.056555	.005335	-.484	.6298
X2TB	1.573344	.158331	8.189E-04	1.370	.1749
X2RTR	-.102320	-.125507	.069996	-1.081	.2833
X3X4	.033929	.105471	.083783	.906	.3678
X3TP	-.296603	-.085484	.006750	-.733	.4659
X3TR	-.072640	-.021781	.007328	-.186	.8529
X3TB	-.077360	-.023256	.007366	-.199	.8430
X3RTR	-.074544	-.129017	.084841	-1.112	.2700
X4NOP	.032252	.088755	.070081	.761	.4489
X4TP	.031329	.085570	.069712	.734	.4654
X4TR	.032002	.086812	.068778	.745	.4589
X4TB	.033042	.091144	.0702[illegible]3	.782	.4368
X4RTR	.019492	.037248	.036993	.318	.7510
NOPTP	.024752	.077081	.079668	.661	.5110
NOPTR	.022256	.066406	.075480	.569	.5714
NOPTB	.034455	.094454	.076791	.811	.4202
NOPRTR	-.003721	-.002099	.025946	-.018	.9857
TPTR	.027967	.080147	.069479	.687	.4943
TPTB	.038169	.105177	.071297	.904	.3692
TPRTR	1.255368	.173850	.001563	1.508	.1358
TRTB	.026097	.077140	.070027	.661	.5107

TABLE 4

*** * * * M U L T I P L E   R E G R E S S I O N * * * ***

Equation Number 3

Multiple R	.93415
R Square	.87263
Adjusted R Square	.86425
Standard Error	6.16347

Analysis of Variance

	DF	Sum of Squares	Mean Square
Regression	5	19780.12433	3956.02487
Residual	76	2887.11155	37.98831

F = 104.13795   Signif F = .0000

------------------ Variables in the Equation ------------------

Variable	B	SE B	95% Confdnce Intrvl B		Beta	F	Sig F
X2TR	-.053307	.009301	-.071832	-.034782	-3.502837	32.846	.0000
TRRTR	.083240	.008869	.065576	.100904	1.272521	88.086	.0000
RTRRTR	-84.313335	16.372069	-116.921137	-51.705533	-.699549	26.521	.0000
X2	61.979441	13.838131	34.418413	89.540468	2.735681	20.060	.0000
X2X2	-3.730340	1.545831	-6.809129	-.651552	-.102082	5.823	.0182
(Constant)	26.214102	2.645538	20.945056	31.483148		98.184	.0000

------------- Variables not in the Equation -------------

Variable	Beta In	Partial	Min Toler	F	Sig F
TR	.046543	.114751	.004483	1.001	.3203
RTR	-.475853	-.107635	.004389	.879	.3515
X2RTR	.142520	.170330	.004359	2.241	.1386
TRTR	.046398	.114083	.004485	.989	.3232

SCATTER OF PREDICTED NO REDUCTION

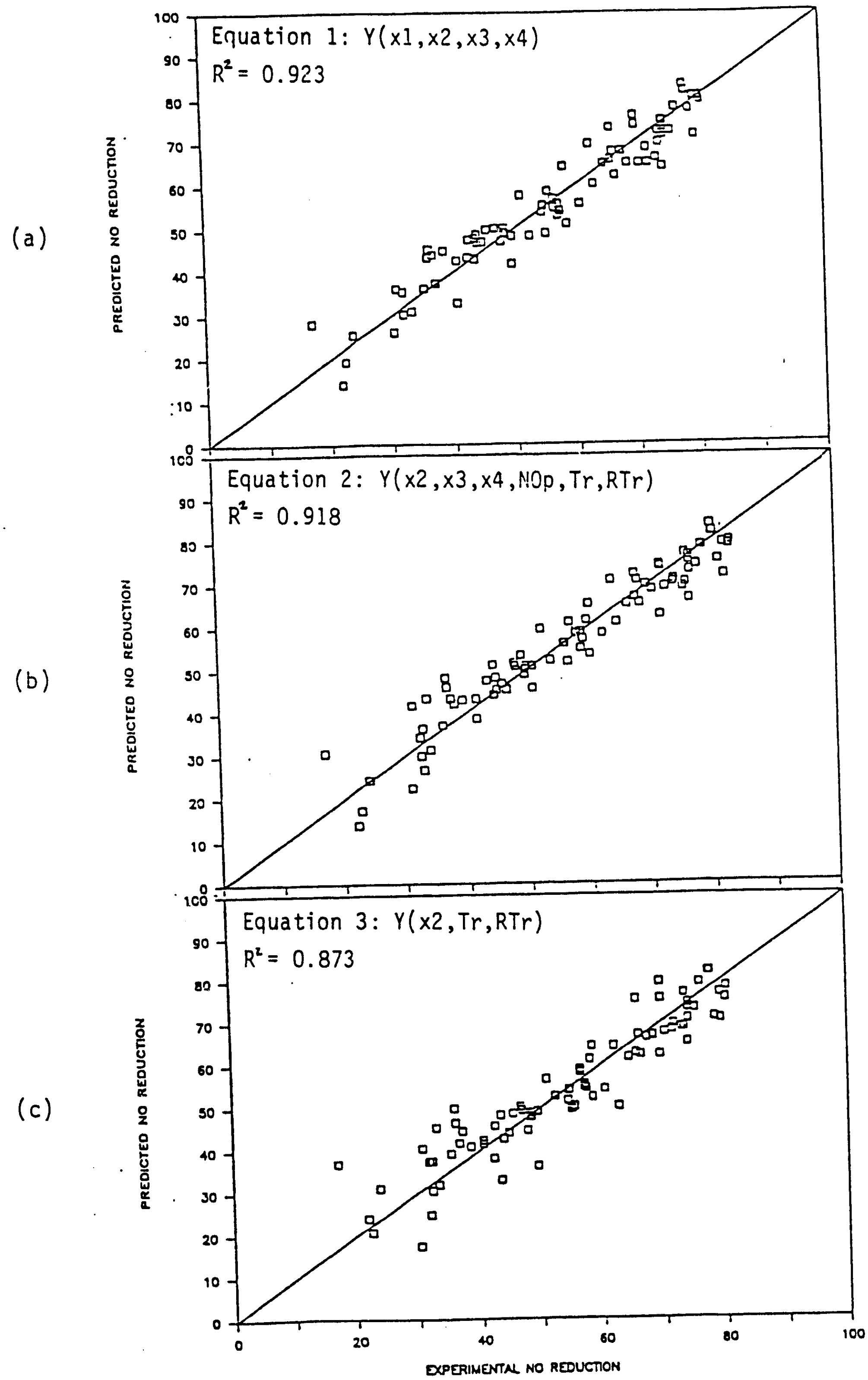


FIGURE 1. Prediction of NO Reduction

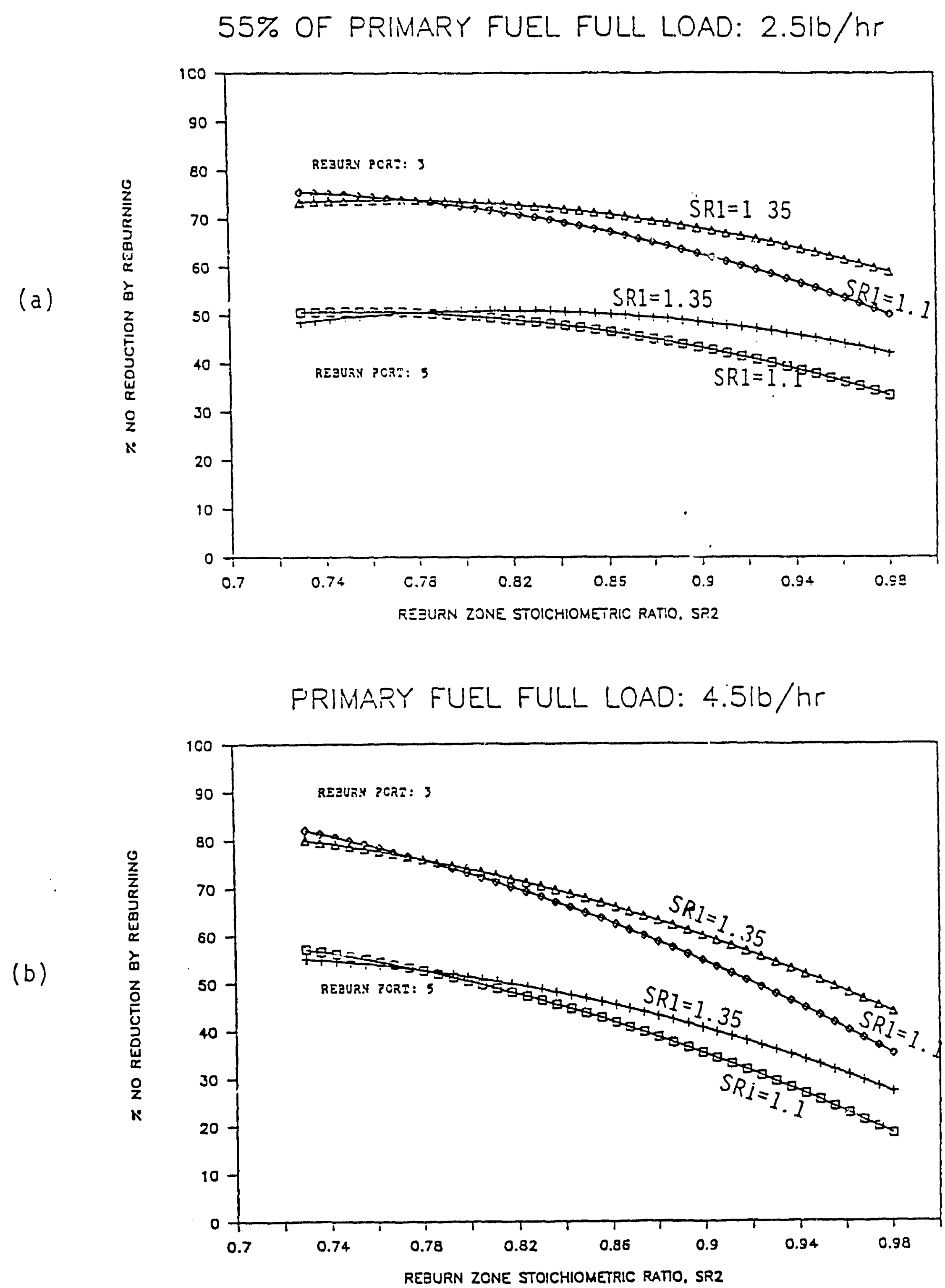


FIGURE 2. Effects of Primary Fuel Load and Primary Stoichiometric Ratio on NO Reduction by Reburning

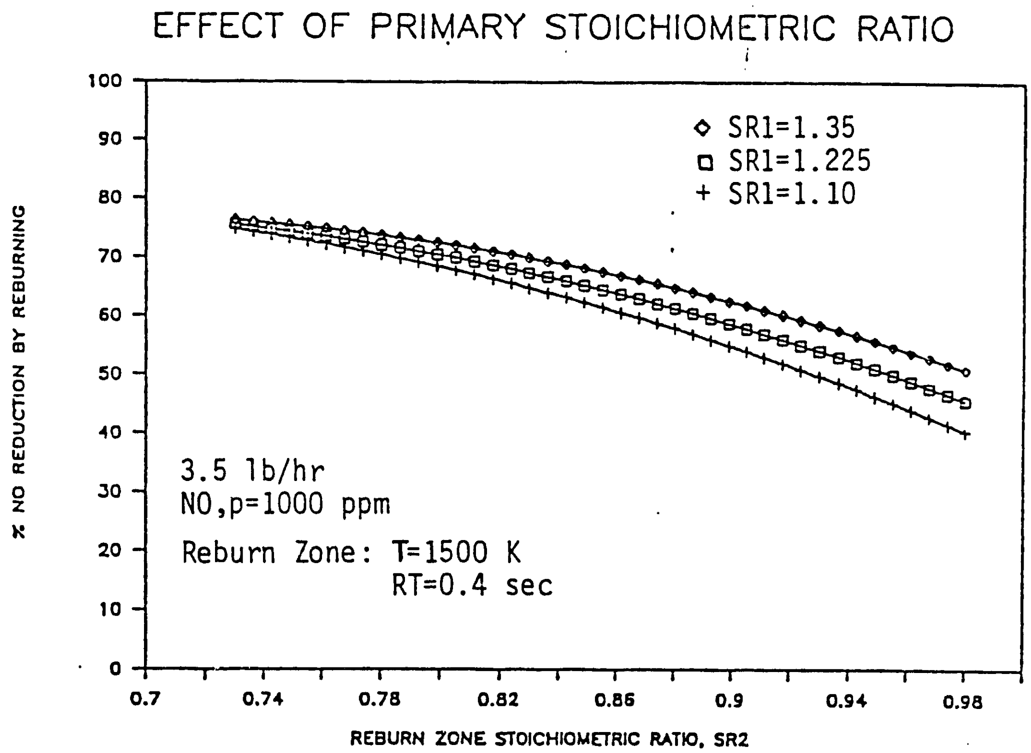


FIGURE 3. Effect of Primary Stoichiometric Ratio on NO Reduction by Reburning

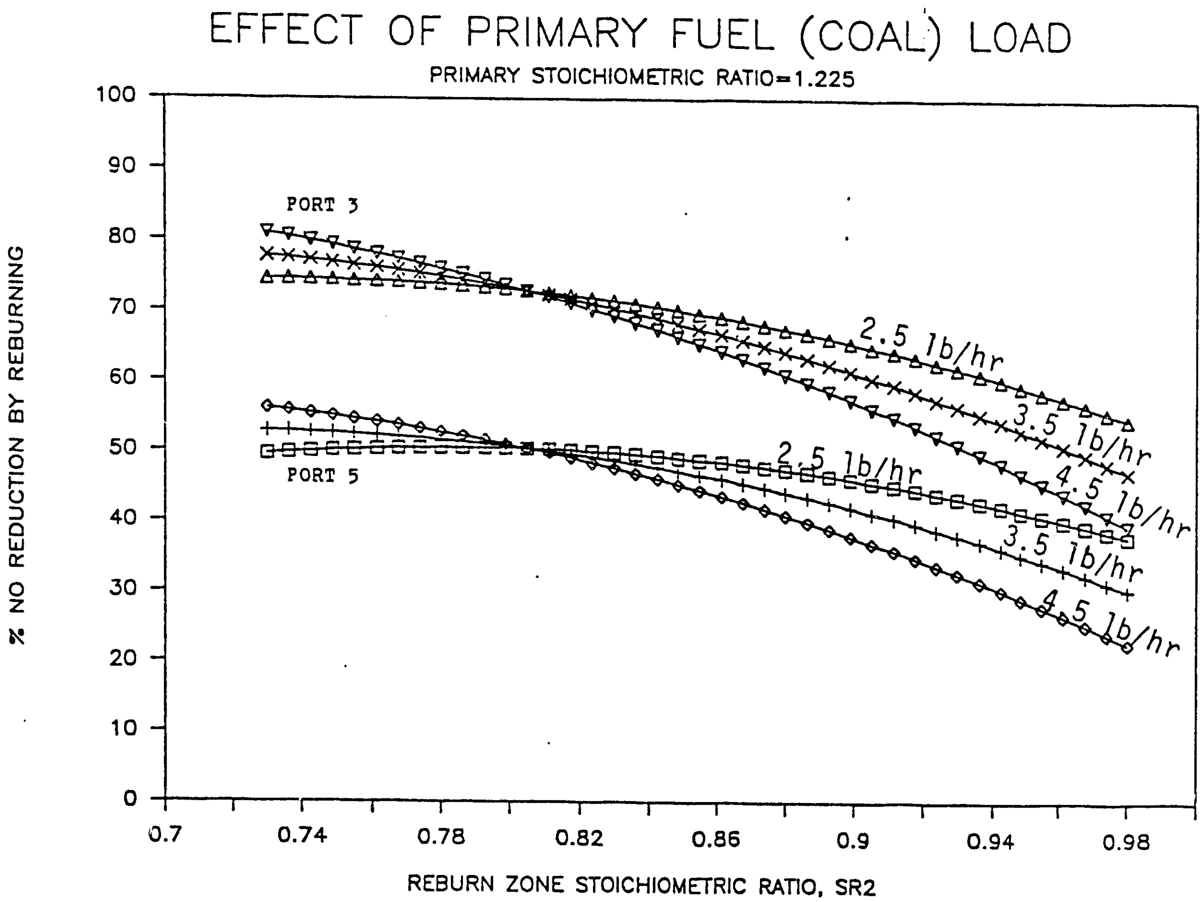


FIGURE 4. Effect of Primary Fuel Load on NO Reduction by Reburning

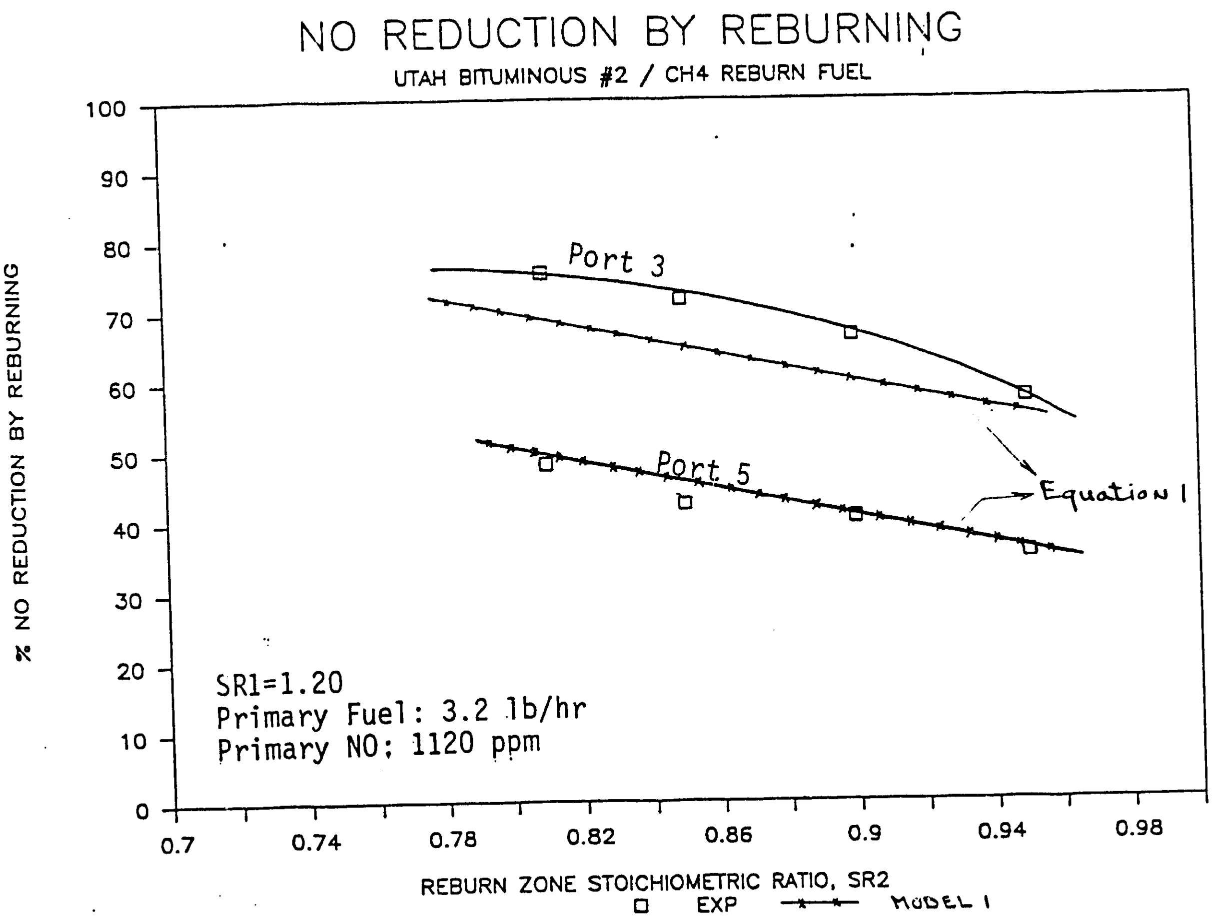
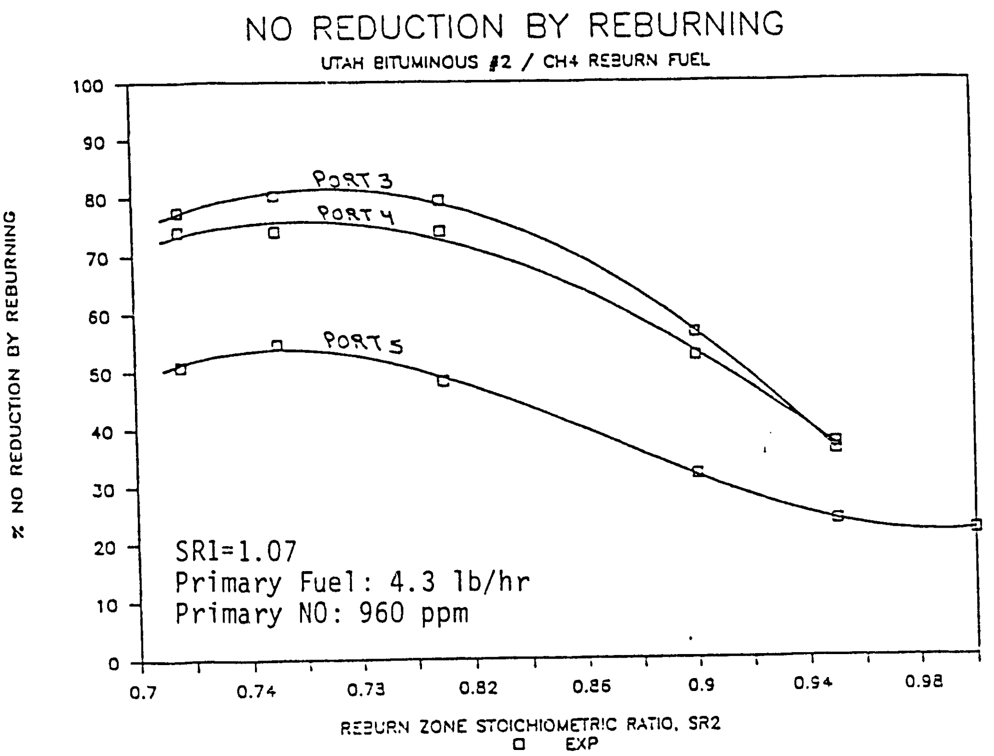


FIGURE 5. Variation of NO Reduction with Reburn Zone Stoichiometric Ratio - Run MR



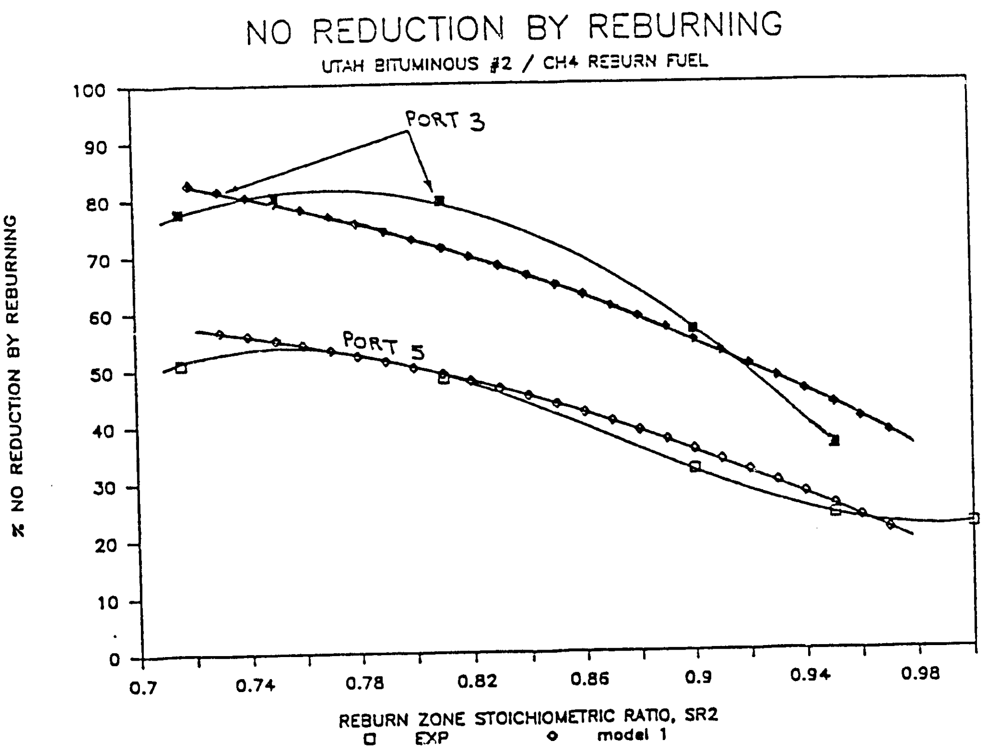


FIGURE 6. Variation of NO Reduction with Reburn Zone Stoichiometric Ratio - Run RV

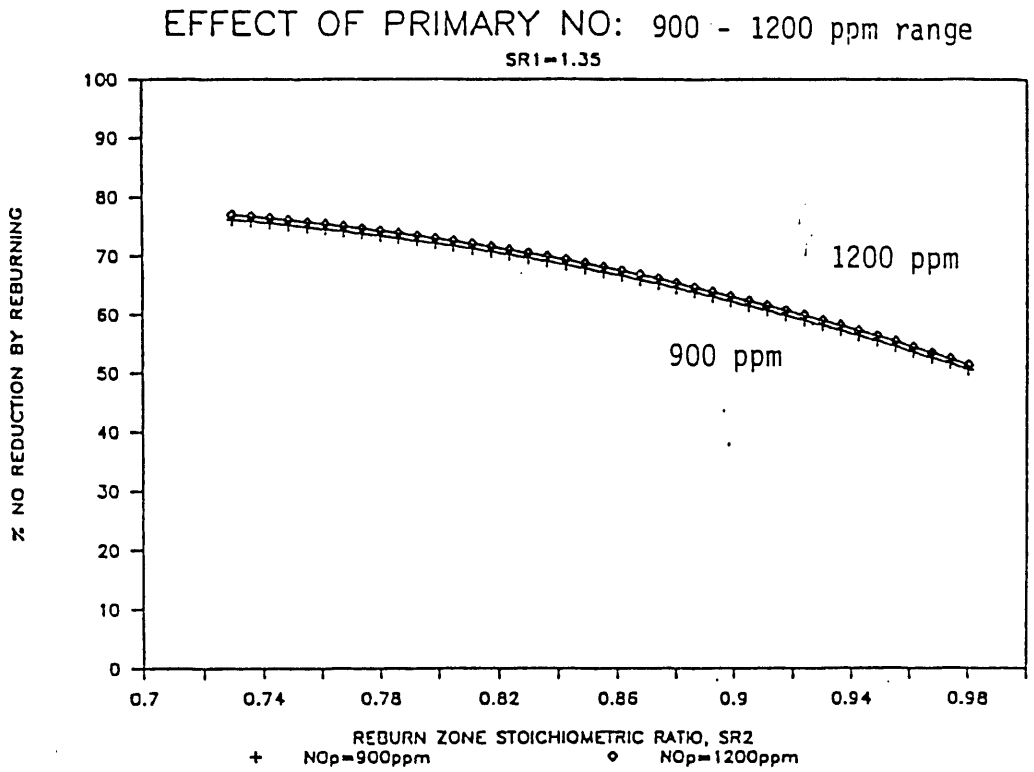


FIGURE 7. Effect of Primary NO on NO Reduction by Reburning

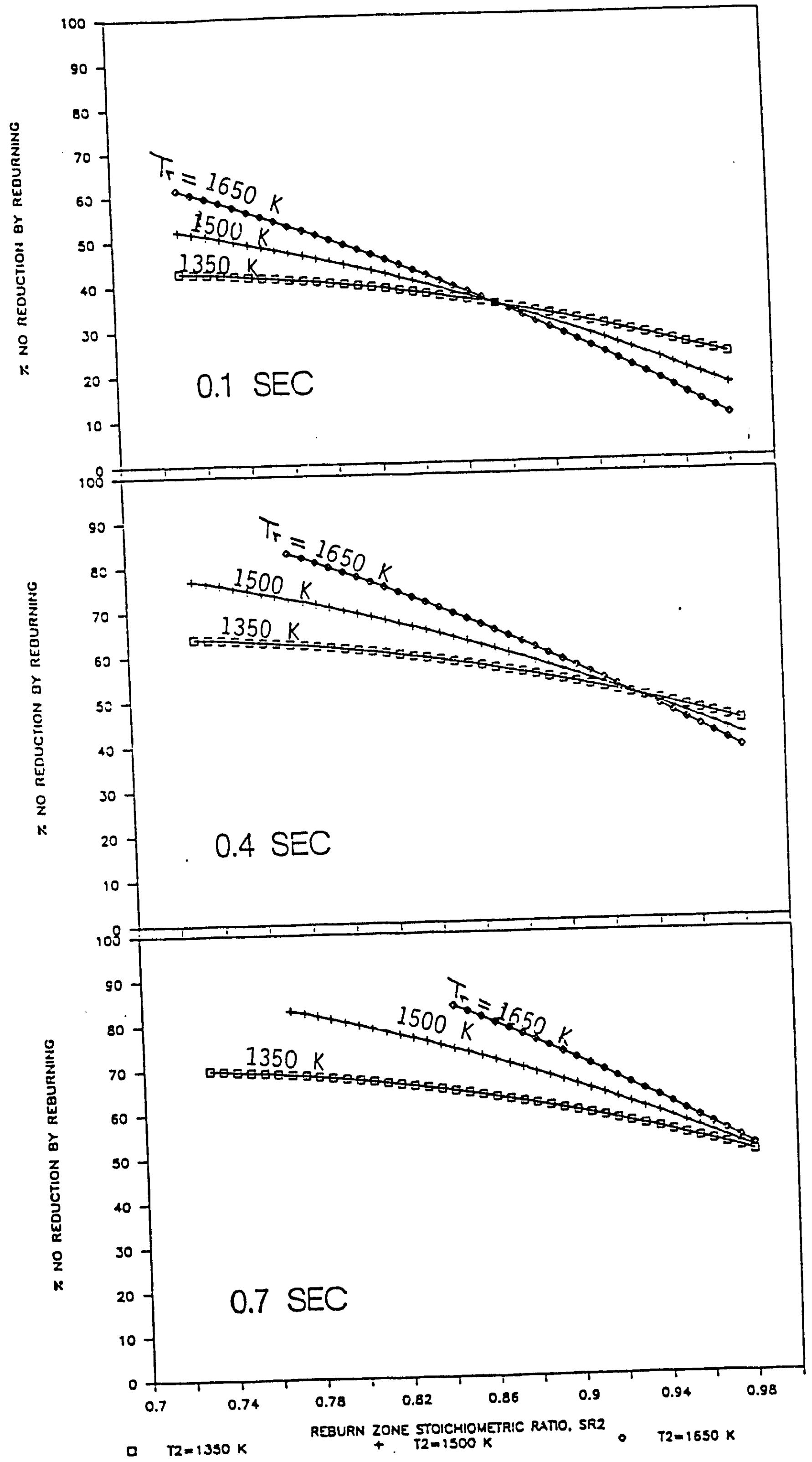


FIGURE 8. Predicted NO Reduction at Different Reburn Zone Residence Times

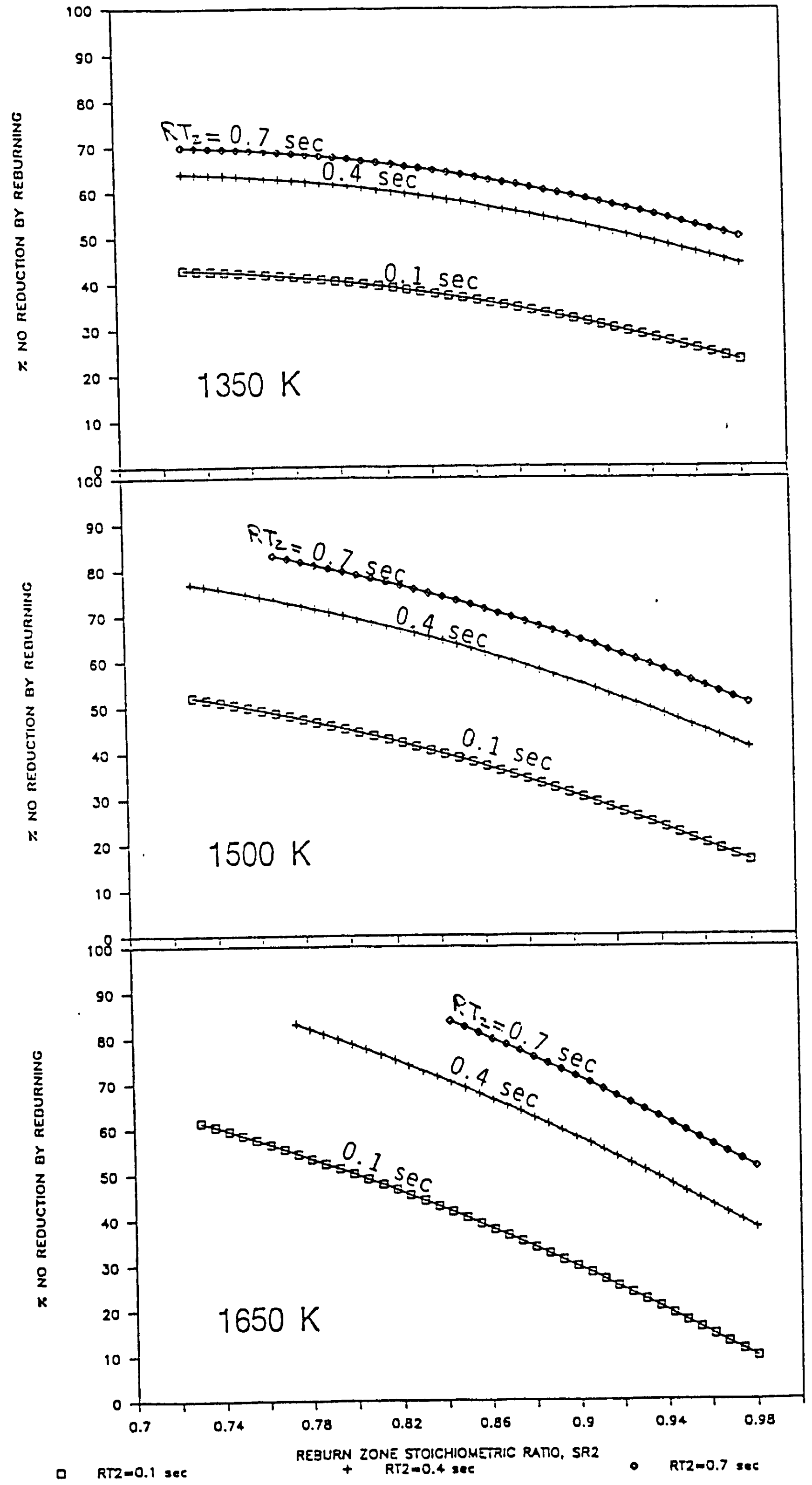


FIGURE 9. Predicted NO Reduction at Different Reburn Zone Temperatures

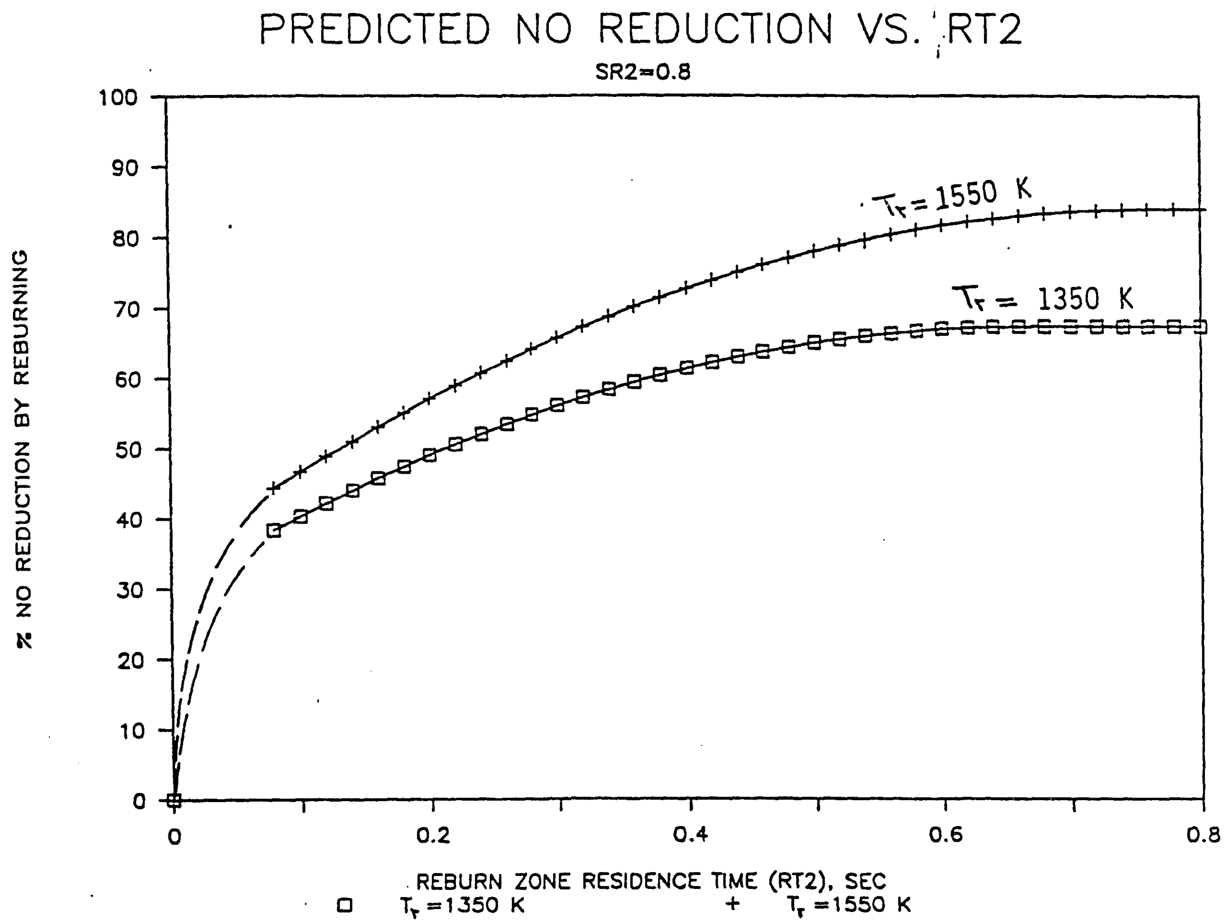


FIGURE 10. Effect of Reburn Zone Residence Time on NO Reduction by Reburning

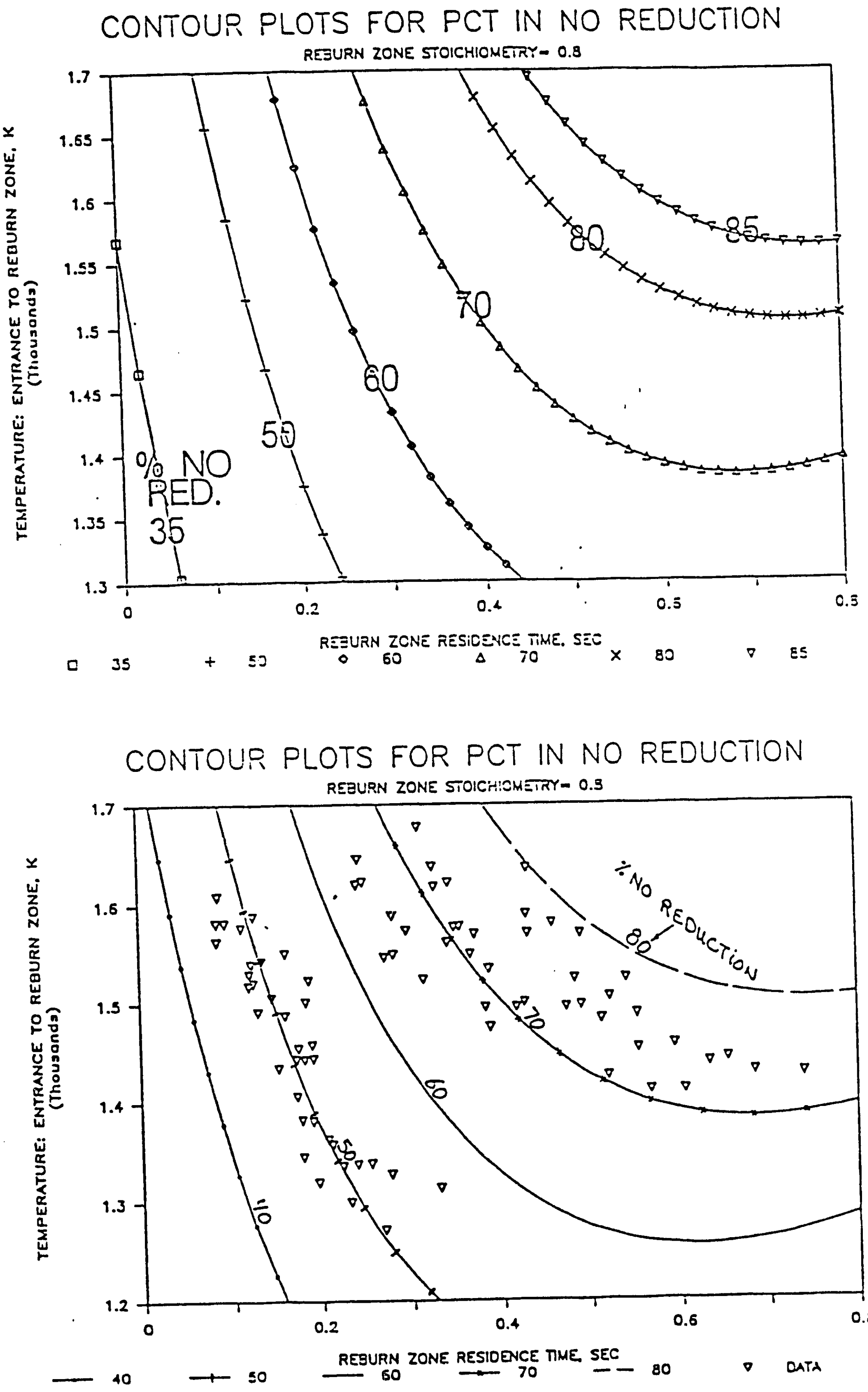


FIGURE 11. Contour Plots for NO Reduction in Terms of Reburn Zone Temperature and Residence Time

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